Chapter 2

CONCEPTS

What Are Structures?

Structures in Your Living Room, Kitchen, Bathroom, and Closet

In Chapter 1, we examined a wide variety of packaging materials, including boxes, bags, and bottles. Each of these is an example of a *structure.* Very simply, a structure is anything designed to hold something up or down, in or out, together or apart. Often people think of structures as very large things, such as bridges, buildings, and towers, but there are lots of structures that are much smaller, easier to understand, and more convenient to study. Discarded packaging materials are readily available and free! In this chapter, we deal first with the more general subject of structures, and then return to packaging as a particularly familiar and interesting category of the larger topic. We'll begin by looking for structures everywhere, just as we began by looking for packaging.

Here are some examples of structures you can find in your home:

- Cups, drinking glasses, plates, and bowls
- Luggage
- Furniture
- Picture frames
- Shoes
- Hooks
- Hangers
- Bars for holding shower curtains, towels, hangers, etc.
- Clotheslines
- Tripods and easels
- Light fixtures
- Umbrellas
- Pipes
- Ladders and step stools
- Pots and pans
- Cardboard tubes found inside toilet-paper and paper-towel rolls
- Anything held together with tape, glue, or string
- Anything that has been sewn, stitched, woven, braided, knitted, or knotted

Structures in Nature

Humans created all of the structures listed above, but we are not the only creatures that make structures. Some structures made by animals include:

- Hives
- Nests
- Spider webs
- Ant hills
- Beaver dams
- Burrows
- Dens and lairs
- Mole hills
- Coral reefs
- Cocoons

Plants and animals are themselves made of structures, and every organism has a long list of structural problems to contend with. A tree, an eggshell, and a fruit are examples of structures. Our own bodies are held up by a complex assortment of structural parts. Some of the structural elements in the human body include:

- Bones
- Muscles
- Tendons
- Ligaments
- Blood vessels
- Skin
- Teeth
- Nails
- Cell walls

Humpty Dumpty, and Other Tales of Structural Failure

How is it that there are so many structures within and around us, but that normally escape our notice? By definition, a structure is something that supports a load. To paraphrase a line from a movie, when a structure does its job, nobody even notices; but when it fails, there's a big mess! Many structures are not supposed to move at all, for example, light fixtures, hooks, and towel racks. Other structures are allowed to move, but only as a complete unit. If you move a chair from one side of the room to the other, it remains intact as a structure. Once the seat gives way, the back comes loose, or one of the legs breaks in half, the structure is no longer effective.

Folding structures, such as folding chairs and umbrellas, are special cases. Here, the parts of the structure are supposed to move, but only in a controlled way, and only when the structure is deliberately being folded and unfolded. At these times, the device is operating as a *mechanism,* not a structure. When someone is sitting on the chair or standing under the umbrella, the parts should not move. Under these circumstances, it is functioning as a structure.

The fact that the parts are not supposed to move is what makes structures difficult to analyze. A structure is composed of parts, just like a mechanism, but it is hard to see where one part ends and the next one begins, because they are not supposed to be "moving parts." When they do move, the structure is said to have failed. Structures become much easier to analyze and understand after they have failed because then you can see some of the parts and how they were once connected.

Structural failure must be of great interest to young children, because, as Petroski (1992) points out, many nursery rhymes deal with structure problems. These include Humpty Dumpty's mishap, Jack's accident descending the hill, Rock-a-Bye-Baby's fall, and the collapse of London Bridge. Adults are also intrigued by the failure of structures, although they would prefer them not to be close by. Much of the enjoyment of action movies, wild-ride documentaries, and slapstick comedies comes from watching cars, planes, buildings, and furniture undergo structural failure.

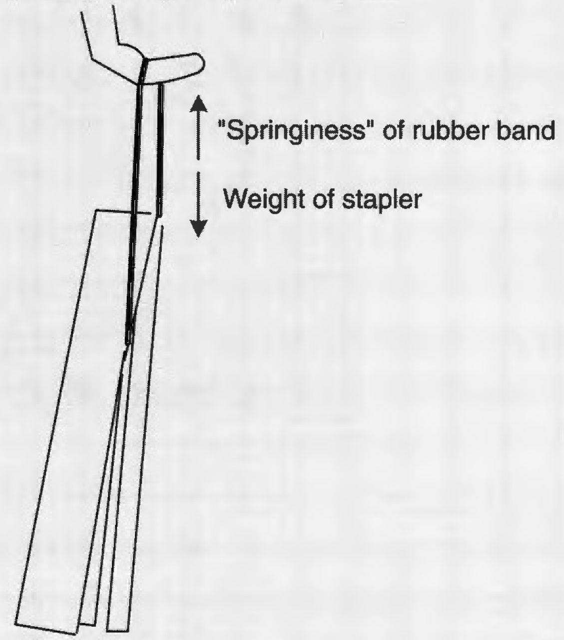
How Structures Work

Saved by the Stretch

When a structure fails, it is no longer able to resist the *forces* that are "trying" to make it give way. These forces are called *loads*. They include gravity, wind, earthquakes, people pushing or pulling, and impacts from other objects. A structure has to "fight back" against the loads that are working to make it fail. How does it do this?

Let's begin with a very simple structure. Take a rubber band, the longest you can find, and loop one end around your finger. Dangle a moderately heavy object, such as a stapler, from the other end (Figure 2-1). The rubber band will probably stretch a little bit, but more than likely, it will hold the stapler suspended. How does it do this?

2-1: **Suspending a stapler by a rubber band**



The arrows at the right side of Figure 2-1 illustrate how. The downward arrow represents the force of gravity on the stapler. The rubber band is the structure; the force of gravity on the stapler is the load, represented by the downward arrow. This is the force responsible for stretching the rubber band. As the rubber band gets longer, it resists, pulling back. This "pulling back" is also a force; it is shown by the arrow pointing upward in Figure 2-1, labeled "Springiness." As the rubber band stretches more and more, the "springiness" becomes greater and greater, until it exactly cancels the load due to gravity. At this point, the "tug-of-war" is a draw, the stapler comes to rest, and is said to have reached *equilibrium.*

Where does "springiness" come from? Anything we call "a solid" has fairly strong bonds between the atoms, which allow it to resist loads far better than a liquid or a gas. A rubber band resists being stretched because the atoms attract one another, and try to restore the material to its original shape. This "restoring force" is what "fights" the load, and makes a structure possible. You can actually see a rubber band stretch, but most materials do not lengthen enough for the change to be visible. However, every material does actually get slightly longer when pulled, whether it is made of string, rope, or steel cable.

Loading something by pulling on it is called *tension,* which comes from the same root as "extend." Simple structures that work in tension are called *ties.* Some common examples of ties are fishing line, shower-curtain rings, luggage straps, yo-yo strings, ceiling fixtures, and elevator cables. A common experience with many ties is that they come loose at the points of attachment. This happens, for example, when a luggage strap tears away from itself near the little clip that is attached to the bag (Figure 2-2).

Stacks Are Structures

Someplace in your house or classroom, you can probably find a pile of things, such as books, papers, CD's, blocks, or boxes. A stack of things is a very simple kind of structure, in which the items near the top are held up by the ones lower down. Figure 2-3 shows the simplest possible stack, where block A is sitting on top of block B.

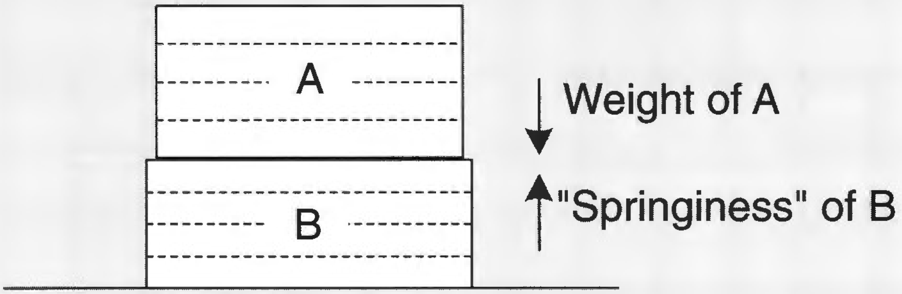
Notice from the diagram that block B is slightly shorter and wider than block A. Before they were stacked, block B looked exactly like block A, but putting a block on top of it made B very slightly shorter and wider. In other words, B is *compressed* by the weight of A above it. The change in shape of B is exaggerated in the drawing, unless B is made of something really flexible, like foam rubber or Jell-O. Most materials would be deformed much less than this, but every material gets compressed at least a tiny bit, even if it is really stiff, like steel, concrete, or stone.

In this example, block B is the structure, and block A is the load. As a result of being compressed like a spring, block B tries to return to its original position. In doing so, it pushes back up on block A. When the upward-pointing "springiness" exactly balances the downward-pointing load, the two forces cancel, and the system is in equilibrium. The block on the bottom is loaded in *compression*, because the load compresses it slightly. As in tension loading, the forces inside the structure work to resist the change from its normal shape. In the rubber band, the forces came from the attraction among atoms being pulled too far apart. In compression, the atoms are being pushed too close together, and their pushing back apart is what makes the structure work.

Stacking is not the most efficient or reliable way to make a *compression structure.* For one thing, the items have to have fairly flat tops and bottoms, or the whole structure may topple. Also, stacking may not provide much resistance against a push from the side. Worse yet, stacking does not use material efficiently. A chair, for example, could be made by stacking material all the way from the seat down to the

2-2: **Shoulder bag strap comming loose at point of attachment**

2-3: **One block supporting another**

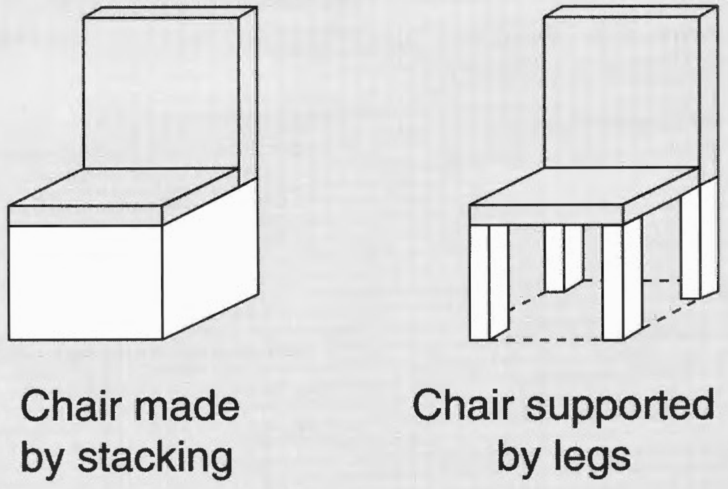


floor, as shown on the left side of Figure 2-4. However, most chairs don't use this type of design. Instead, they use only four legs to support the load, as shown on the right side of Figure 2-4, and eliminate the rest of the material within the dashed lines. The four legs can provide enough resistance in compression, but with much less material.

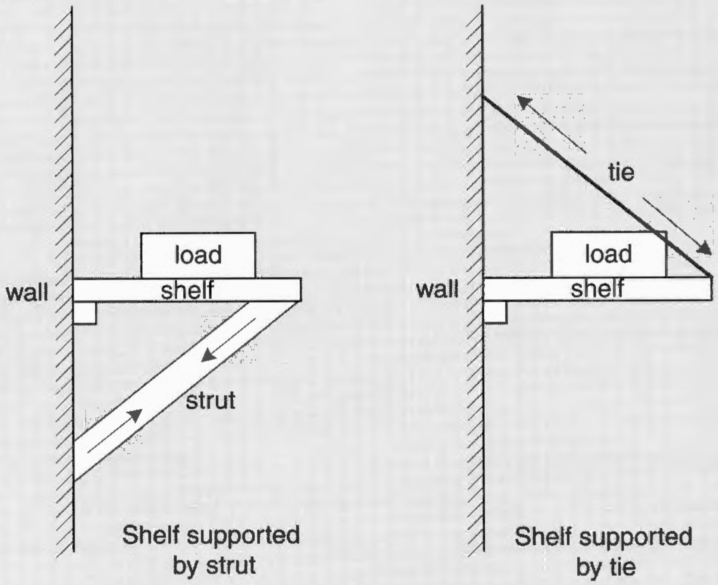
Simple compression elements, such as chair legs, are called *struts*. Other examples of compression elements are the central pole of an umbrella, the legs of a tripod or easel, the vertical parts of a bicycle frame, the side pieces of a bookshelf or ladder, columns in a building, and the pole of a floor lamp or fan. Some structures can be supported using either struts or ties. Figure 2-5 shows an example. The left side shows a side view of a shelf, supported from below by a strut. On the right side, a similar shelf is suspended from a tie. The arrows show the forces of compression in the strut and tension in the tie. Which method—struts or ties—works better? Ties have the disadvantage of requiring special connections to other parts of the structure, while struts are at least partly self-supporting, thanks to gravity. Furthermore, ties don't usually create as rigid a structure as struts. In Figure 2-5, the suspended shelf on the right could fold upwards slightly, while the strut-supported shelf on the right has much less room for movement.

On the other hand, struts also have their disadvantages. The taller a strut is, the wider it has to be to avoid the chance of buckling, as we shall see. The trunks of tall trees have much larger diameters than short ones. Ties don't have this problem. A piece of string, fishing line, wire, chain, or spider web material will support the same amount of weight regardless of how long it is. Vogel (1998) points out that nature tends to prefer ties, while human designers are more likely to go with struts.

2-4: **A chair made by stacking (left) and using legs (right)**



2-5: **A shelf can be supported by a strut (left) or a tie (right)**



Giving Shear Its Due

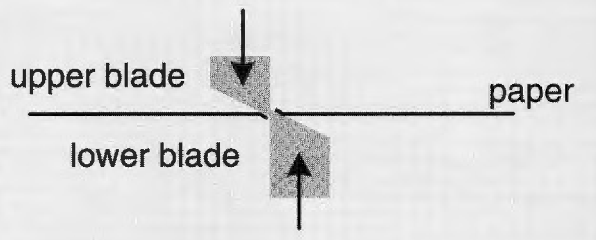
Most discussions of structures emphasize tension and compression, which are the two fundamental forms of loading. However, there is another kind of loading that is often more important, particularly in daily life.

Begin to cut a piece of paper with a pair of scissors. Now look at the two scissor blades head on (Figure 2-6). Note, first of all, the inclined plane cut into the each of the blades. These are simple machines, which are designed to reduce the amount of force needed to make the cut. (See ***Stuff That Works!,*** *Mechanisms and Other Systems.)*

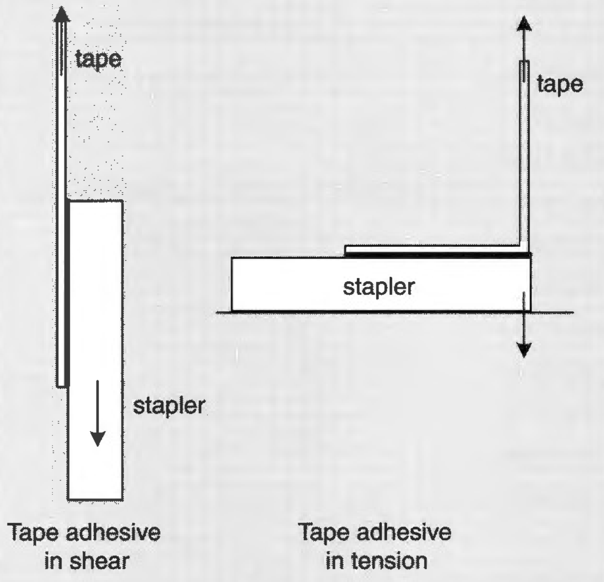
Next, notice how the blades move, as shown by the two arrows in the diagram. At first sight, this looks like compression, because the blades are moving towards each other. However, compression would not result in cutting the paper. Note that the arrows don't point towards each other, as they would have to in compression. The upper blade moves down somewhat to the left of where the lower blade moves up. This combination is called *shear*, which is easy to remember because "shears" is just another word for scissors. When you use a pair of scissors to cut a piece of paper, you are applying a shear load that is more than the paper can resist. If the paper could resist the load, it would stay intact. Tearing is another way to overcome the paper's shear resistance.

Many structures have to support loads in shear, and therefore need to be able to resist shear. How do shear resistance and tension resistance compare? Here is an experiment you can do, using a little tape and a stapler, or a similar object of about the same weight, to compare the shear and tension resistance of a piece of tape.

2-6: **Scissors poised to cut paper**



2-7: **Two ways to lift a stapler with a piece of tape**



Cut a piece of masking tape or cellophane tape about six inches long. Press a few inches of the tape firmly on the flat side of the stapler, leaving a few inches of tape extending beyond it. Now hold the free end of the tape vertically, and lift the stapler with it, as shown on the left side of Figure 2-7. The tape will likely support the stapler. If not, simply press the tape more firmly, or reposition it so more of its surface is in contact with the stapler. Next, place the stapler on a table, so it is lying on the side opposite the tape, as shown on the right side of Figure 2-7. Again, try to lift the stapler with the tape. More than likely, the tape will pull off, leaving the stapler behind.

Why? A piece of tape is simply a strip of paper with an adhesive on one side. In Figure 2-7, the heavy black line represents the adhesive. In the first part of the experiment, the pull on the tape, represented by the upward-pointing arrow, is to the left of the downward-pointing arrow that symbolizes the weight of the stapler. As with the scissors, the two forces are not aligned. They operate on the left and right sides of the adhesive coating of the tape, which is therefore loaded in shear. The tape holds because the adhesive has good shear resistance.

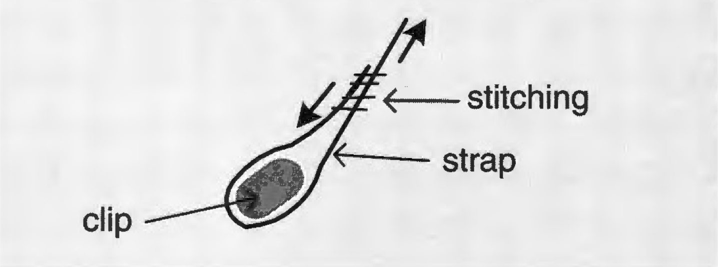
Now, let's look at what happened in the second part of the experiment. The force up on the adhesive was directly above the downward weight of part of the stapler, as shown on the right side of Figure 2-7. This time, the adhesive was loaded in tension, which it cannot resist very well, and it gave way. As a result, the tape lifted off the stapler because the adhesive couldn't resist the tension.

In discussing ties, we noted that one disadvantage of these structures is the problem of making secure attachments. Ties don't usually fail in tension, because strings, ropes, chains, straps, and wires are pretty strong. They usually separate at the points of attachment, and shear is nearly always the culprit. The luggage strap in Figure 2-2, for example, didn't fail in tension. The strap was originally looped around the clip, and then sewn to itself, as shown in Figure 2-8. When the weight of the bag was too great, this pulled down on the short end of the strap; meanwhile the long end was held in place by someone's shoulder. This combination set up shear forces on either side of the stitched attachment, shown by the heavy arrows. These shear forces made the strap separate from itself at the stitching.

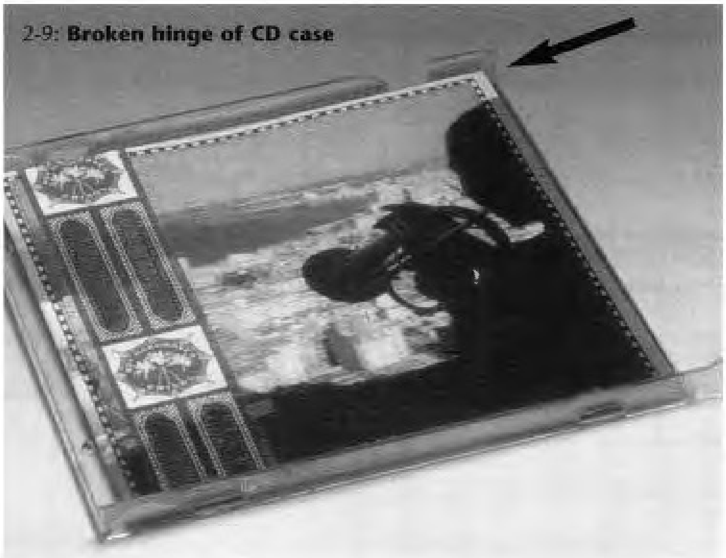
Shear is at its worst where a part protrudes from the main body, as in the hinges of a CD case; or where a protruding part is attached to a flat base, as with a car's side view mirror. Shear failure accounts for many annoying little problems:

- Broken hinges of CD cases (Figure 2-9)
- Broken handles of pots, pans, cups, and pitchers
- Buttons and snaps that pop off clothing because the thread unravels
- Wires and cables that pull out of computers, stereos, and other electronic gear
- Knobs that pull off their shafts
- Side-view mirrors that come off cars
- Door stops that separate from the wall
- Shoelaces that tear out the side of the shoelace hole (Figure 2-10), etc.

2-8: **Detail showing shear failure of shoulder bag strap**



2-9: **Broken hinge of CD case**



2-10: **Shoelace that has torn through the side of the hole**

Common demonstrations of tension and compression involve two people supporting each other in two different ways. In the demonstration of compression, the two lean towards one another and support each other by pushing their palms together (Figure 2-11). If you do this experiment with another person, try to pick someone roughly the same size as you. As you lean together, you will feel the compressive forces in your arms.

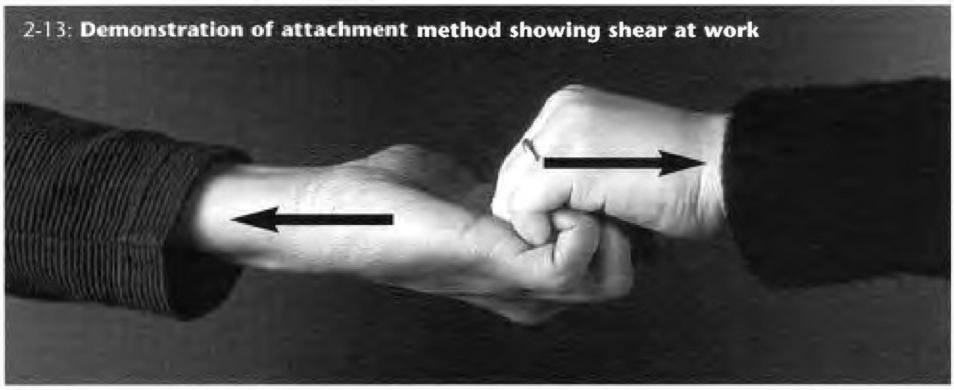
The other demonstration, used as an example of tension, has the two people leaning away from each other and supporting one another by pulling on one another's hands (Figure 2-12). Again, you should do this with someone roughly the same size. This one is a little trickier, so lean back slowly until you are both sure of your footing. Sure enough, when you are in position, you can clearly feel the tension in your arms.

However, the demonstration in Figure 2-12 actually involves more than tension. As with all tension structures, there has to be a point of attachment, which is loaded in shear. In the demonstration shown in Figure 2-12, the attachment point is where the two hands meet. The hands are attached by having each person curl his or her fingers around the other person's, as shown in Figure 2-13. As they lean back, not only do they feel tension in their arms, but also a force in each hand that is trying to unravel the fingers. As the photograph shows, this force is a shear force. The so-called "tension demonstration" is really a demonstration of shear as well as tension.

2-11: **A Two-person structure, arms loaded in compression**

2-12: **A two-person structure, arms loaded in tension**

2-13: **Demonstration of attachment method showing shear at work**



Fascinating Fasteners

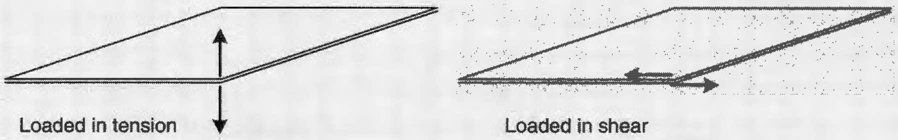
Some of the most important parts of structures are fasteners, which are devices specially designed to hold parts together. Fasteners are widely used for packaging, construction, decorating, and keeping things organized. The most commonly used fasteners for joining wood are nails and screws. Wood can also be joined using glue. For paper or cardboard, some fastener choices are thumbtacks, paper clips, and staples. Another possibility is to use some kind of spring clip, such as a "bulldog" clip, the clip found on a clipboard, or the "press" clips inside some binders. Other binders use loose-leaf rings or spiral-shaped wire. Glue or tape can be used as well. Figuring out the best way to keep papers together is a structures problem.

We will focus on how the loose-leaf ring, the paper clip, staple, and binder clip work to hold papers together. What kinds of loading do they resist well or not so well? To answer this question, suppose you need to join two sheets of paper together at one corner. A tension load would try to lift the top sheet vertically, while shear loading would tend to make one page slide horizontally over the other (Figure 2-14).

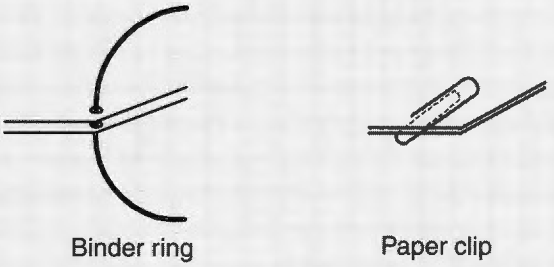
Now, suppose the two sheets are joined by a loose-leaf ring (Figure 2-15, left). The ring does not prevent the top piece from being lifted off the bottom piece. In other words, it offers no resistance to tension. On the other hand, it does resist shear loading, because the metal binder prevents the pages from being shifted sideways very far. The page can move horizontally only by tearing, which can be a problem with loose-leafs. What happens in this case is similar to the shoelace tear-out problem shown in Figure 2-10. If the paper tears, it's because the force exceeds the shear strength of the paper itself.

The situation with the paper clip is exactly the opposite. It offers little resistance to sliding motion, because the top piece could easily slip out from under the paper clip; but it would not easily permit the top piece to lift right off (Figure 2-15, right). The loose-leaf ring passes vertically through the paper, so it resists horizontal loading. The paper clip, on the other hand, has horizontal wire loops that prevent vertical but not horizontal movement.

2-14: **Two ways of separating two sheets of paper**



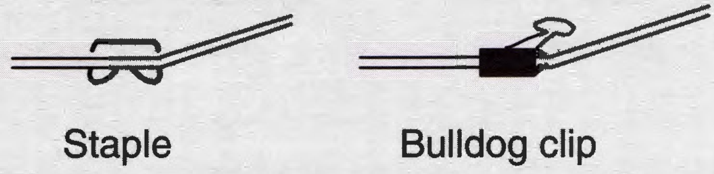
2-15: **Two sheets of paper joined by a ring (left) and a paper clip (right)**



Next, consider what a staple does. The two papers can move neither vertically nor horizontally because the staple offers resistance against both shear and tension. It is sort of like a combination of a binder ring and a paper clip, running first horizontally, then vertically, and then horizontally again. Staples are also very cheap. Their major drawback is that they require a special tool (a stapler) to insert them and form them into their remarkable shape. A spring clip also provides both kinds of resistance, but for a different reason. The spring exerts enough force to prevent the two sheets from moving either vertically or horizontally (Figure 2-16).

The most common fasteners for joining wood are the nail and the screw. Suppose a nail joins two boards, one on top of the other. Like a loose-leaf ring, its vertical shaft prevents sideways motion, and it therefore resists shear. However, a nail is fairly easy to pull out, so its resistance to tension is not so good. A screw, on the other hand, permits neither horizontal nor vertical movement, because the threads prevent it from being pulled out easily. Like a staple, it resists both tension and shear.

2-16: **Using a staple (left) and a bulldog clip (right) to join two pages**



Problems with Shelves, and with Beams in General

Are you always short of storage space? Shelves provide an easy solution to many common storage problems, and are a very useful kind of structure. If you don't have enough storage space, you can make your own shelves using tape and recycled cardboard (Figure 2-17). There are some obvious problems with this design, but they can easily be fixed. Homemade shelves may not look as nice as the manufactured variety, but they are easier to repair, and the materials are mostly free!

A structure like a shelf, which is held in place at either end, and loaded in the middle, is called a *beam*. Other examples of beams include most tabletops, chair seats, ladder rungs, and slats for holding up mattresses or bedsprings. The loading of a beam combines all of the types we have been discussing: tension, compression, and shear.

Let's look at what happened to the shelves in Figure 2-17. At A, two shelves on the left have broken free of their supports. Here is a typical attachment problem, in which the original tape support has failed. Next, notice the shelf on the right (B) that is sagging under its load. This shelf is supported at both ends, but the weight has distorted its shape, especially near the middle. This shelf is experiencing both tension and compression.

We'll consider the attachment problem first. You can learn a lot about attachment issues just by looking at some commercially-made shelves to see how they are supported. Some common attachment methods are:

2-17: **Homemade shelves**

- screws or bolts, passing through the vertical side into the shelf, as are often found in steel shelving units;
- little brackets that hang the shelf from above, by means of slots cut into the sides, as exist in some storage cabinets;
- little pins or platforms that rest in holes on the sides, and support the shelves from below, as in most bookcases;
- one-piece molded construction, which forms the shelf out of the same piece as the side supports, as in most refrigerator door shelves.

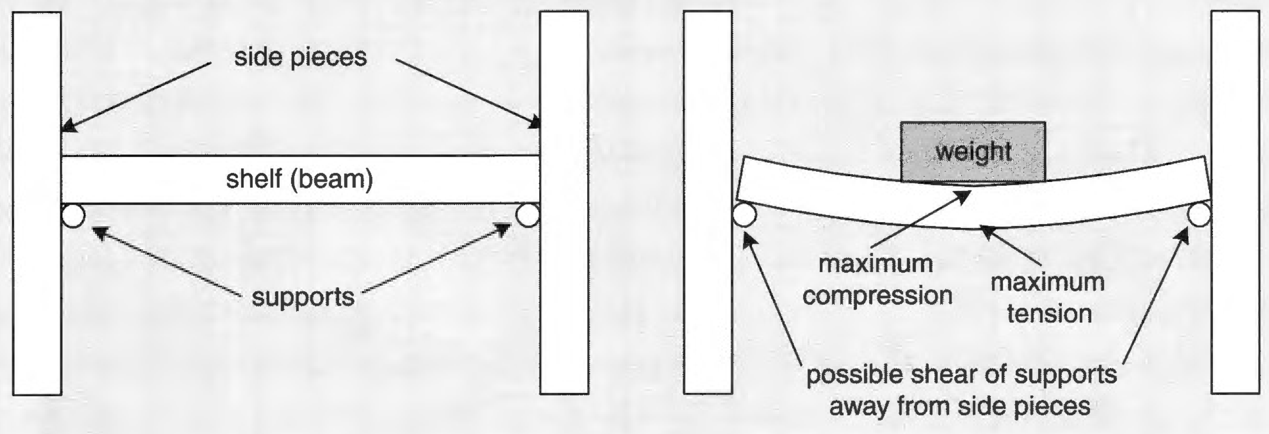
Whatever method is used, the primary job of a shelf support is to resist shear, hopefully better than the failed supports in Figure 2-17.

Next, we'll turn to the bending problem. To clarify what happens to a shelf under load, Figure 2-18 shows a beam whose bending has been exaggerated.

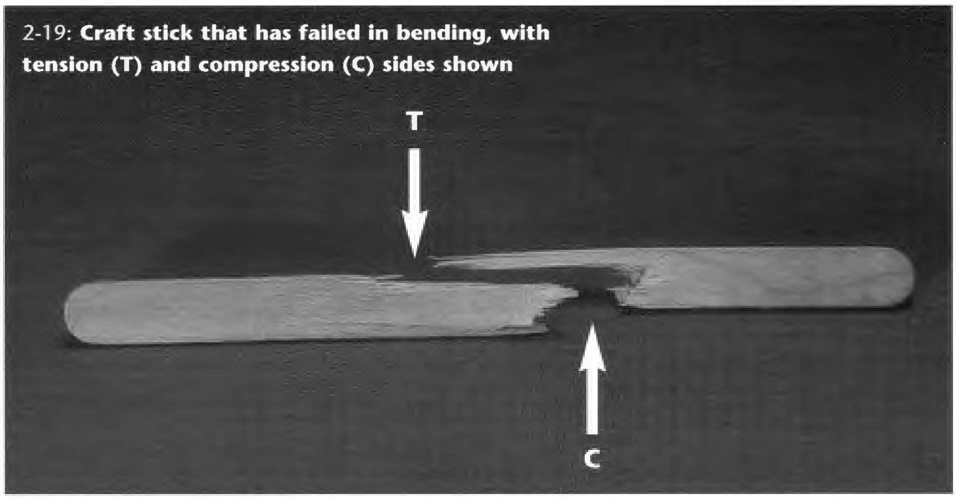
There are several things to notice about the beam in the diagram. The supports experience maximum shear, because they have to resist the downward weight of the load. Notice also that as the beam bends, the part on top is forced to become shorter, while that on the bottom becomes longer. As a result, the upper half is loaded in compression, while the bottom half is loaded in tension. The maximum tension is along the very bottom surface, while the maximum compression is along the top surface, because those places are where the distortion is the greatest.

Here is a little experiment you can do to see how tension and compression make beams break. Grasp a small piece of wood, such as a craft stick, with one end in either hand. Now, push the middle with your thumbs until the wood breaks. Examine the broken halves carefully (Figure 2-19). The side your thumbs were on is like the top of the beam in Figure 2-18. Its wood fibers were in compression. The broken fibers on this side are short, and you can probably find some that folded back on themselves. On the side away from your thumbs, the wood fibers were loaded in tension. The long jagged edges are wood fibers that were originally connected, but pulled away from each other due to the tensile loading. Because these fibers are very strong in tension, they tend to fail by slipping away from each other, in shear, rather than by breaking, which happens on the compression side. That's why the jagged edges are so much longer on the tension side.

2-18: **Typical beam, unloaded (left) and under load (right)**



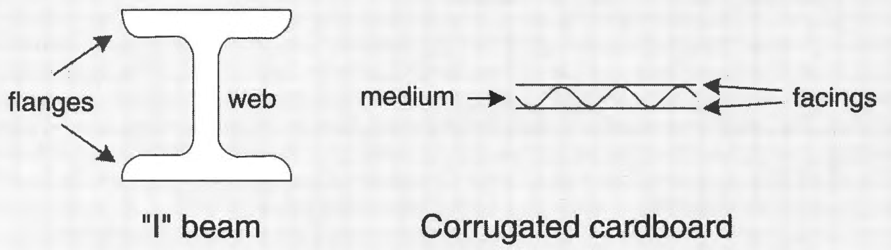
2-19: Craft stick that has failed in bending, with tension (T) and compression (C) sides shown



Because the worst areas for compression and tension are at the top and bottom, respectively, these are the parts of a beam that need to have the greatest resistance. The center of the beam doesn't need to do nearly as much. In the construction industry, the most common beams have a cross-section shaped like the letter "I" and are called *I-beams.* Figure 2-20 (left) shows the end view of an I-beam. Most of the material is contained in the top and bottom flanges. The slender center, called the *web*, serves mostly to join the flanges, which offer nearly all of the resistance to compression and tension.

A similar strategy is used in making cardboard cartons. Most cardboard used in packaging is corrugated, and has the cross-section shown in Figure 2-20 (right). The flat top and bottom, which are called *facings*, are made of cardboard that is nearly twice as heavy as the corrugated part in the middle, which is called the *medium.* The facings are like the top and bottom flanges of an I-beam; they offer most of the resistance to bending. The medium is similar to the web; its job is mostly to hold the top and bottom together, using as little material as necessary.

2-20: **An I-beam (left) and a piece of corrugated cardboard (right)**



What Can Go Wrong in Compression

So far, we have looked at structural elements that have to resist tension or shear. In some ways, compressive loads are easier to work with. The earliest monuments built by humans, and the largest ones still standing, were built mostly by piling large blocks on one another. These include the Pyramids, the Great Wall of China, and the Roman aqueducts. Piling things on top of one another sounds simple enough, and it avoids the attachment problem, but large blocks are heavy and hard to move. Nowadays, most compression structures use much less material, as in the chair of Figure 2-4.

A vertical strut, much thinner than it is tall, is called a *column.* The legs of a table, chair, stool, or tripod and the sides of a bookshelf or a ladder are all columns. A big problem with all of these structures is that the columns have to remain more or less vertical. When the legs give way by slipping outward, they are said to *splay.*

Ladders have horizontal ties to keep the two sides from splaying (Figure 2-21). Most chairs, tables, tripods, and easels use techniques of one kind or another to prevent splaying. These include:

- "X" shaped cross braces to prevent sideways movement;
- slots that hold the legs captive under a tabletop or chair;
- chains or straps that work as ties to keep the legs of a tripod or easel in place;
- rings around the outside of stool legs, holding them together.

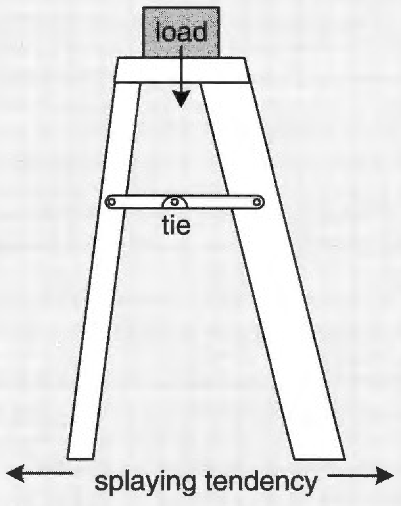
It's worth looking at a few chairs and tables to see how the designers tried to keep the legs from splaying.

A second problem with columns is that they can bend, just like beams. When a column bends under load, the problem is called *buckling*. Figure 2-22 shows why a yardstick does not make a good cane: it buckles under the weight of the user. To prevent buckling, a column needs to have a lot of material on its outsides. In fact, the best shape for buckling resistance is about the same as for a beam. For that reason, I-beams, stood on end, are used to make columns in buildings, and corrugated cardboard is used for the sides of cartons, as well as for the tops and bottoms.

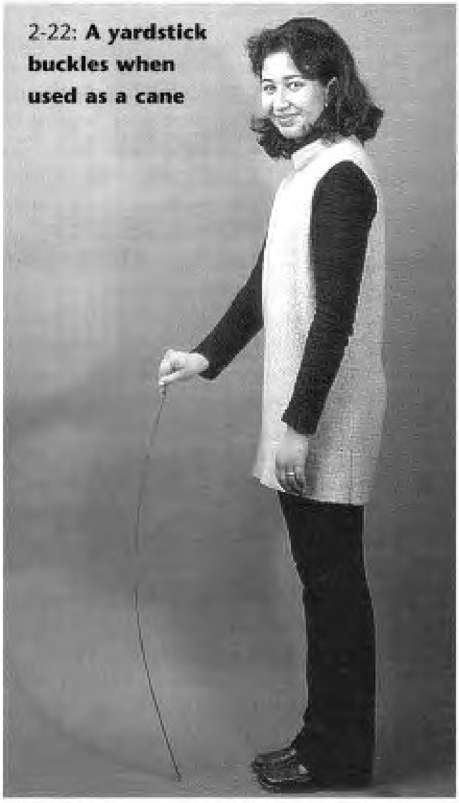
However, there is one very big difference between bending and buckling. A beam can bend a little, and still support a load, as the sagging shelf does in Figure 2-17. Bending a little can actually make the beam stronger. On the other hand, when a column buckles, it's usually all over. Even a very slight amount of buckling makes a column weaker, so it buckles more and more and gives way almost instantly!

The ancient Romans came up with a clever answer to the problems of building with beams and columns. They fashioned a beam and two columns out of one piece of material, and rounded it on the inside. The resulting structure is called an *arch* (Figure 2-23). It is a structure that works almost entirely in compression. There is an arch inside each of your feet. Together, your two arches have to support your entire body weight. Related to the arch, and even stronger, is the structure you get by rotating an arch around its center: the *dome*. Both the top and bottom of an eggshell are domes, which make an egg very difficult to break at the ends.

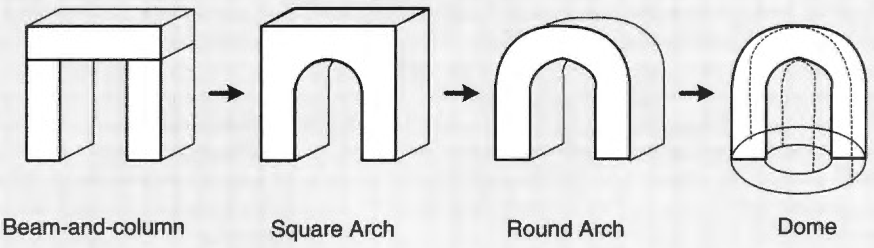
2-21: **Side view of ladder, showing tie to prevent splaying**



2-22: **A yardstick buckles when used as a cane**



2-23: **From beam-and-columns to arch to dome**



Exploring Packaging

Materials You Can Find Anyplace

Packaging is everywhere. It encloses nearly everything people buy, carry with them, send to one another, and store. Sometimes, these packages work well, in which case they are barely noticed. Often, packaging fails in one way or another, at which point it becomes an annoyance. In either case, people rarely stop to examine or think about this extraordinarily important and common branch of technology.

Packaging and containers are not usually included in what people think of as technology. In a thought-provoking argument, Lewis Mumford (1967) suggests that this omission reflects a male bias. Containers are associated with traditionally female occupations, such as cooking, brewing, and gardening. Tools and weapons, in contrast, are more related to typically male pursuits like hunting, metalworking, and tool-making.

Although packaging issues are largely beneath conscious notice, at times they assume great importance, for both children and adults. Many children are very particular about the styles of bookbags or water bottles they will take with them, while adults have strong preferences and beliefs in selecting shopping bags, boxes, and luggage. These beliefs are generally untested. Do you really know which of your shopping bags is strongest?

Most people take containers for granted, but they are taken very seriously by major manufacturers. The sales volume of corrugated cardboard boxes is considered a barometer for the health of the entire economy. Approximately 100 billion jars and bottles, and their caps or tops, are sold in the U.S. annually. Another 100 billion beverage cans change hands. In the soft-drink industry, the package is considered more important than the beverage it contains. Both the aluminum "pop-top" can and the plastic bottle were considered major, highly profitable innovations in the soda business. In many parts of the world, soda is transferred to a plastic bag before being sold to the customer. The can or bottle is simply too valuable to give away!

Besides being a major industry, packaging is a fertile curriculum area. The materials are free, consisting of discarded items. They are very familiar to children and adults. Packaging problems abound in our daily lives, which provide a multitude of opportunities to analyze and redesign existing packages, and design new ones. These activities offer a host of connections with other areas of the curriculum, including language arts, social studies, science, and math.

Children enjoy writing about their discoveries and inventions related to packaging. The evolution of packaging and beliefs about it, offer a window into profound changes in our society. Analysis and design of boxes offers an engaging route into measurement, as well as plane and solid geometry. Product testing of packages invokes an array of science process issues, such as control of variables. The mechanical properties of packaging raise basic issues of structures, such as stability, compression, tension, shear and energy absorption. Packaging can be a vehicle for curriculum integration.

What Good Are Packages?

Nearly every commercial package is a carefully engineered product, cleverly designed to solve an impressive set of problems. A useful starting point in analyzing a package is: "What was this package designed to do?" Each package has a different set of tasks to fulfill, which is why there are so many different kinds of packages. Here are the kinds of needs that packages are supposed to fulfill:

2-24: **Carton that barely holds its contents**

1. **The package has to contain the product.** The most obvious function of a package is to keep the contents in one place and (if it is solid) in one piece. The most apparent packaging failures occur when the package seems about to stop keeping the product inside (Figure 2-24). Containment of the product can be complicated by conditions inside and outside the package. The plastic soda bottle, for example, has to withstand inside pressures reaching 5 or 6 times atmospheric, at temperatures ranging from below freezing to well above 100°F.

2. **The package should maintain its shape during shipping and storage.** Shoppers are usually reluctant to buy dented cans, although the product may not have been affected in any way. In addition, cans and cartons are often stacked high on one another for storage, shipment, or display. The ones near the bottom have to support the weight of those above them. They need to be strong enough in compression to do so, or the entire stack may fall. Of course, some packages are not expected to keep their shape—for example, bags.

3. **The package may need to protect the contents from the environment.** This requirement is particularly important for food and beverages, which can spoil in a variety of ways. A small juice carton, which is shipped and stored at room temperature, has layers of plastic, paper, ink, and aluminum, each with a different purpose. To see this for yourself, cut an empty juice box open and pull apart the layers. The paper makes the box rigid, and holds the ink; the ink provides decoration and information; the aluminum keeps out light, oxygen, and microorganisms; and the plastic keeps the liquid from oozing out. Until this carton was developed, juice could not be sold in unrefrigerated boxes, because it had an unfortunate tendency to ferment and explode!

   Often the need to protect the contents conflicts with the need for access (see #4, below). The small juice container is intended for one-time use, so reclosure is not an issue. However, many packages are too big for their contents to be consumed all at once. Many cracker and dry cereal packages use the "bag-in-box" strategy, which features a reclosable inner bag to keep out moisture, because atmospheric humidity can lead to a loss of crispness. Sometimes the cardboard top is also equipped with a reclosable tab-in-slot.

4. **The package should permit access to the product.** A container is useless if it is too difficult to open. The earliest metal cans, which were made of heavy iron, were normally opened with a hammer and chisel. Some modern packages seem pretty hard to open, but others are equipped with convenient dispensing devices, such as squeeze tops, straws, pump and spray dispensers, measuring cups, one-at-a-time tissue paper dispensers, etc.

5. **Some packages have to control access to product.** Access is not necessarily for everybody. Many foods and drugs now come in "tamper-evident" packages, which signal the shopper if they have already been opened. There are a variety of ways of doing this: outer seals, inner seals, tear bands, mechanical "breakaway" seals (Figure 2-25), and vacuum buttons are all common. There are also "child-resistant" tops, used most commonly in packaging medicines. Common technologies include the "push-then-turn" top, the "squeeze-then-turn" top, and the "line-up-the arrows" top (Figure 2-26). These have to be hard enough to open that small children won't get into them, but not so hard that elderly or infirm patients are kept out.

6. **"Point-of-sale" packages (those displayed in stores) usually promote the product.** Before modern packaging was developed, goods were delivered to stores in bulk barrels and drums, and the storekeeper had to help with each purchase. Packaging made it possible for shoppers to select items themselves, in the self-service market, now called the supermarket. On a typical hour-long visit to the supermarket, you see about 30,000 different products, or about 10 per second. All of them are competing for your attention. Marketing professionals regard the package as the "punch line" of a marketing campaign—their very last chance to grab your attention before you make that final choice. A tremendous amount of time and expense goes into the graphic design of those packages. This aspect of packaging is covered in the ***Stuff That Works!*** curriculum guide, *Signs, Symbols, and Codes.*

7. **Most packages also provide information.** There are many kinds of information that might appear on a package. Some of this information, such as the box certificate (see Figure 1-20 in Chapter 1) and the bar code, is not directed towards the consumer. The box certificate contains a message from the box manufacturer to the shipper. The bar code

2-25: **Tamper-evident "breakaway" seal on a bottle**

2-26: **An assortment of child-resistant tops**

is read by a computer and winds up in the store's database. The "Nutrition Facts" box, required by the U.S. Government on most food items, does provide information for the consumer. Many packages also have instructions, recipes, phone numbers, and other information for the user who cares to look. Recycling numbers, discussed in Appendix A, provide information to the consumer as well as to others involved in the recycling process.

8. **The package should have minimal environmental consequences to humans and other organisms.** The harm caused by certain packaging materials has led to the elimination of some technologies. Some early attempts to make plastic soda bottles failed because they were suspected of releasing toxic by-products. The earliest pop-tops had a removable tab that was both a source of litter and also a health hazard to birds, fish, and barefoot humans. As a result, the removable top was replaced by one which remains with the can (Figure 2-27).

Looking at this list, it is obvious that most packages have more than one set of requirements to satisfy. The answer to "What was this package designed to do?" hardly ever has only one answer. On the other hand, some criteria are more important than others. For example, if a package can't hold its contents, it hardly matters what kind of information it conveys!


2-27: **Non-removable pop-top**


2-28: **Blister pack**

A Feeling for Packages: Surveying Strengths and Weaknesses

Once the criteria for evaluating a package have been established, it is reasonable to ask: "How well does the package meet these criteria?" In looking at any package, there will be some obvious ways in which it works or doesn't work.

Every package has been designed by someone to solve a problem. It may also create new problems. Those horribly hard-to-open "blister packs" (Figure 2-28) are good examples. Most blister packages hold the product with an over-sized card in a clear bubble of plastic. The purposes of these packages are to:

- Make the product and promotional material visible;
- Provide a large surface area, making the package harder to steal;
- Make it difficult to remove the product from the package, further discouraging shoplifting.

These last two design goals are examples of controlling access. They are also what make these packages so irritating—the product is hard to remove from the package, even when it has been legally acquired! Some styles of blister packages try to overcome this problem by providing perforated doors in the back of the cardboard, or by allowing the cardboard to slide off of the plastic top, or by providing a tab or break for easy opening.

Another example of problematic design is the "gabletop" container, which is used for milk, juice, and other liquid products. These containers are made of paper coated with plastic on both the inside and outside, sometimes with additional layers of plastic and aluminum foil inside. A quart or half-gallon is rarely consumed at one sitting, so these packages need to be resealable. At the same time, milk is easily spoiled, and the container has to provide a good barrier to light and oxygen, even after it has been opened the first time.

As with many other packages, the gabletops present a conflict between the goals of protection and access. The conventional milk container is opened by pulling both sides of the gable back until they are flat, and then opening them in the reverse direction so a pour spout forms. This can be very hard to do, especially for small children. Opening these cartons often leaves behind torn corners and ragged edges, which make it hard to pour the contents without dribbling (Figure 2-29). Probably as a result of these problems, some dairies and juice companies have come out with gabletop containers with screw-off tops (Figure 1-3 in Chapter 1). These usually have an inner seal, which is removed the first time the container is used.

2-29: **Gabletop, obviously opened with difficulty**

How Does It Measure Up?

The question "How well does it work?" is pretty vague. There is rarely only one way to solve a packaging problem. There are nearly always alternative packages that are designed to do more or less the same thing. The question "How well does it work?" can be reformulated as "How does this package compare with alternatives?"

Comparing designs is a familiar task from science education, where units on product testing are intended to teach control of variables and fair testing. Product testing of packages arises from everyday questions: Which bag is strongest? Which cushioning material works best? Which pump dispenser is fastest? These issues come up frequently and the answers are often of practical importance.

Bags

Bag testing is an easy-to-do activity, which yields nearly immediate results. Add weights to each bag gradually, until it breaks. Some shopping bags are pretty strong, so you may need a lot of weight to break them. Weightlifting weights are useful for this purpose—they are heavy, have no sharp corners, and have the amount of weight stamped right on them.

What are the variables that need to be controlled in this experiment? One is the way the bags are supported; another is the way the weights are added. If they are dropped rather than carefully placed in the bag, the impact will have a greater effect than the gentle addition of weight. Weights with sharp edges or corners can puncture the side of the bag, creating a new area of weakness.

Weightlifting weights are not always the best type of weight for bag testing. They can pose a safety hazard with younger children, and are also difficult to transport. As an alternative, some teachers have used plastic one- or two-liter soda bottles filled with water. If a bottle drops on someone's foot, it will not cause injury. A liter of water weighs one kilogram, so this type of weight can also lead to a discussion of the metric system. Also, empty soda bottles are readily available and free, and can be transported empty, which makes it easier to bring them into the classroom. On the other hand, bottles of water may not be heavy enough to break a bag. If you use these as weights, select relatively flimsy bags to test. Another strategy is to hold the bags by only one handle, which should require only half the weight, if the handles are the weakest links. With paper bags, you can also reduce the necessary weight by testing the bags wet rather than dry.

Testing results can be surprising. Bags often fail at the handles, so handle attachment methods can be very important (Figure 2-30). Most people assume that plastic bags are stronger than paper ones, but we have found paper shopping bags that hold well over 100 pounds. In Appendix A we discuss some of the different ways in which bags break.

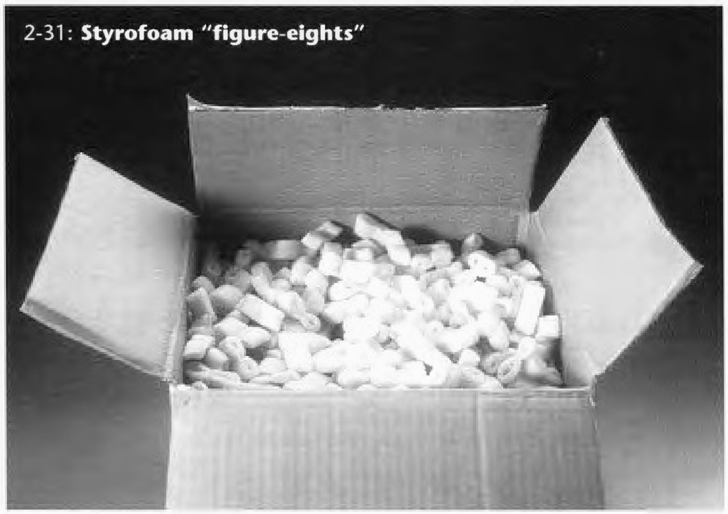
Cushioning

Another fascinating area for product testing is comparing cushioning materials. These come in a wide variety of types. Inside of packages you can find spongy paper or cardboard padding; bubble wrap; Styrofoam sheets, blocks, end caps, "peanuts" or "figure eights" (Figure 2-31); crumpled or shredded newspaper; or even plastic bags filled with air (Figure 2-32).

These air-filled bags may be difficult to find, but you can make them yourself by blowing up plastic sandwich bags and tying them tight, like balloons. The messy wadding material used in book mailers consists of untreated paper fibers and bits of shredded newspaper.

2-30: **Shopping bag collection, showing many different handle types**

2-31: **Styrofoam "figure-eights"**



2-32: **Minimalism in cushioning: the air-filled bag**

To test cushioning material, you will need a standard fragile object, which the cushioning is supposed to protect. Most people think immediately of eggs, but these are problematic for several reasons. One is that they are very messy when they break. Also, raw eggs are sources of harmful bacteria, which can lead to food poisoning if hands aren't washed with hot soapy water. Also, eggs are no longer useable after they break, which means that food is wasted.

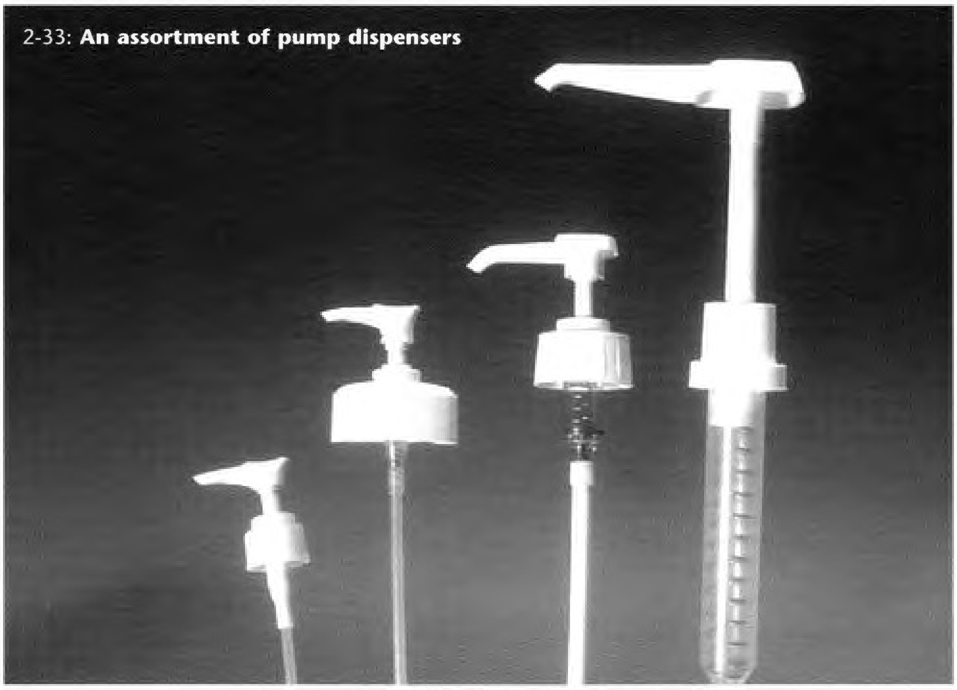
For these reasons, we have come up with several alternative to eggs as fragile products for testing cushioning. Some teachers have used water balloons, but these are messy too, and it is hard to get exactly the same volume each time. Another idea we had was to roll out thin lengths of modeling clay, and allowing it to dry without firing it. However, real modeling clay (not plasticene) is no longer so easy to find. The best alternative we have found are snack items, such as very thin breadsticks, crackers, and chips, which are often found broken when the box is first opened. These can be wrapped in foil, wax paper, or paper towels to keep them edible after the test. Some other possibilities are chalk and mechanical pencil leads.

How should the test proceed? For control of variables, identical boxes should be used and identical amounts of cushioning material. To find out which cushioning technology is most effective, the boxes can be dropped from increasing heights, or increasing amounts of weight can be dropped onto them. These methods are not equivalent. Again, the results can be surprising. Some background on cushioning materials is presented in Appendix A.

Pump Dispensers

A third example of product testing involves pump dispensers. These come in a wide variety of types and sizes. You can find them on top of containers for hand soap, condiments, cleaning supplies. and other products (Figure 2-33). These fluids vary greatly in *viscosity*, or resistance to flow. Depending on the viscosity and the type of nozzle, the fluid may come out as a glob, a stream, or droplets. The amount that comes out each time will vary, depending on the dispenser as well as the fluid. Often, a pump dispenser needs to be primed a few times before any product will come out. There are a lot of issues here, which can be studied systematically through controlled product testing.

2-33: **An assortment of pump dispensers**



To experiment with pump dispensers, it is not necessary to use the same fluid or the same container they came with. We have found it convenient to place the tube in an open pan of fluid. After experimenting with them for a while, children will think of their own criteria for evaluating their performance.

In Christine Smith's sixth-grade class, the students came up with these performance criteria (see Chapter 4):

- How many times do you have to prime the pump before anything comes out?
- Once the fluid starts coming out, what is the average amount per stroke?
- How far does the stream of fluid travel?

One path of exploration is to test a variety of pump dispensers with the same fluid. Water is the most obvious choice. Alternatively, you can use the same pump dispenser and test a variety of fluids of different viscosities. Possible fluids include water, alcohol, mineral oil, corn syrup, etc. We examine how pump dispensers work in Appendix A.

Package Design, Redesign, and Re-use

Having analyzed and tested a package, and discovered its weaknesses, it makes sense to ask: "How could this package be redesigned to do a better job?"

If the package has already failed, the better question might be "How can this package be repaired, so it can still be used?" These two questions are not so different. Redesigning a package so it won't break usually involves reinforcing the very areas that are most likely to fail, before they actually do. "Repair" means doing pretty much the same thing after the failure has occurred.

One outcome of bag testing is that you will find yourself with lots of broken bags. They can break in a variety of ways, as we shall discuss in Appendix A. A pre-K/K class established a "Bag Repair Area" for fixing the broken bags. In the process, they learned how to identify how each bag had failed. Then they looked for ways to reinforce the bags so they wouldn't break so easily. These children were learning redesign at a very young age!

Another aspect of package design is to look for new uses for a package that has been discarded. Most environmental education programs focus on recycling as the solution to the solid waste problem, but re-use is both more beneficial to the environment and has more educational potential. Recycling is not so easy to learn about at an elementary level. For example, the recycling of plastic soda bottles into fleece pullover sweaters is a high-tech process involving a large investment and extensive technical know-how. Children can certainly collect soda bottles, but there is little else about recycling that is really accessible to them.

On the other hand, re-use of packaging material requires little or no expenditure, nor much prior background knowledge. For example, some sixth-grade classes decided to construct a model city out of re-used packaging materials. Their first step was to look for discarded materials, and think about or test the properties of what they found. Re-using old packages in new ways is a real challenge to the imagination. For example, the squeeze-dispenser top of a bottle of dishwashing detergent became the nose of a locomotive in the model city. Another example comes from a teacher workshop. One participant quietly walked over to the door and shut off the lights. On the worktable, for all to see, was the lamp she had made from a discarded wire spool. These are two creative examples of re-use.

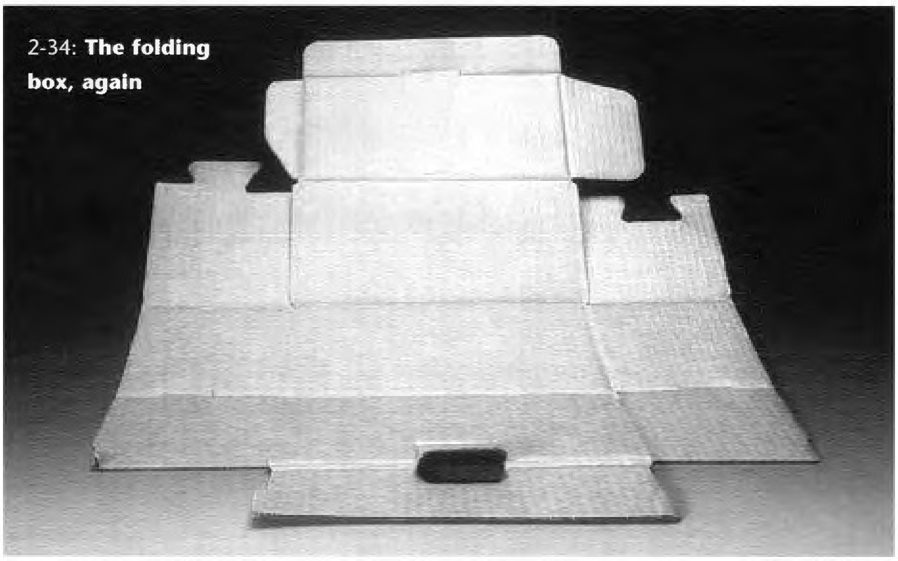
A third category of design involves creating something new. Of course no design is really "from scratch." A designer always brings knowledge of existing designs with her in thinking about a "new" design problem. For this reason, there is no clear-cut distinction between "redesign" and "new design." An example of a design problem that draws heavily on an existing design is the following:

> You will be provided with a folding box that can be unfolded flat and refolded, without tape or glue (Figure 2-34). Using the same basic design, draw, cut and construct a package for a block of a different size.

This problem requires considerable measurement, 2-D and 3-D geometry, and spatial visualization.

The most authentic type of design problem is one that arises naturally in the course of children's lives. Sandra Skea's sixth-grade math students designed and made portable storage units to hold shoebox dioramas that had to be carried from class to class (see Chapter 4). A fifth-grade class designed see-through packages to both display and promote T-shirts they were selling as part of a school-wide poetry festival. A group of sixth-grade science students designed and made packages for fragile gift items they had made in class. Each of these projects began with design criteria that had arisen from a real need. Each group's design could be tested against these criteria, compared with the products of other groups, and redesigned and retested, if necessary.

All design projects can and should draw on existing designs. Looking carefully at someone else's design and drawing conclusions from it is what we call analysis. The connection between analysis and design happens when data from existing designs is used to inform a "new" design. Some teachers in a workshop decided to construct shelving units from discarded cardboard, tape, and string. They were unsure about how to support the shelves on the vertical side panels. To answer this question, they examined all of the cabinets, blackboards, desks, and bookshelves in the workshop area to find out how this problem had been solved in each of these units. They found about a dozen fundamentally different solutions, which provided many ideas for their own design problem.



2-34: **The folding box, again**